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IMAGE PROCESSING ALGORITHMS FOR KKVS WITH IR IMAGING SENSORS

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Abstract

Image processing algorithms enable a kinetic kill vehicle (KKV) with an IR imaging sensor to intercept a missile warhead in space. The algorithms are required to determine the target position soon enough and with such accuracy that the KKV can divert itself toward a successful impact. This is affected by 1) target brightness, shape, rotational motion, and associated objects such as debris, 2) sensor characteristics including aperture size and signal-to-noise ratios, 3) the KKV's divert capability and IMU accuracy, and 4) the acquisition range and closing velocity for the target relative to the KKV. Furthermore, the algorithms are constrained to run on embedded digital signal processing (DSP) hardware with finite throughput and memory capacity.

This paper presents image processing algorithms for KKVs with IR imaging sensors and describes 1) the fundamental requirement for target position estimates, 2) the three potentially most difficult parts of the problem (detection, selection, and aimpoint), 3) various algorithms that can be used, and 4) partitioning the algorithms for implementation in multi-microprocessor subsystems.

1 Introduction

The KKV mission is to destroy a missile warhead which may still be attached to the launch vehicle, or perhaps a stage of that vehicle, or else the warhead may be a detached re-entry vehicle (RV). The ability of a KKV system to defend against the attack is dependent upon 1) the surveillance system's ability to detect a threat, 2) the accuracy with which ground or airborne control can vector the boost vehicle towards the kill point, 3) the boost vehicle's deployment envelope, 4) the KKV thrusters' ability to remove remaining errors, 5) the guidance, navigation and control (GN&C) system accuracy, and 6) the capability of the KKV's sensor and image processing. This paper considers only requirements for topic 6).

The KKV cannot, in general, impact a warhead at an exact point. Errors from thrusters, attitude control, and computation result in an impact some distance from the desired point. The distance between the desired and actual impact points will be referred to as the miss distance. The allowable miss distance, which defines the kill region on the target, can be extended backwards in time to define a surface that would result from utilizing the maximum KKV capability. If the target is acquired at a long range, then the divert capability can be used early in the mission to remove a relatively large initial miss distance with an initial lateral delta velocity that is integrated over the remainder of the mission. Since the surface is reduced by image processing errors, the errors should cause a negligible contribution to the decrease in surface size.

The image processing algorithms must determine the target line-of-sight (LOS) in an accurate and timely manner so that the KKV can divert to intercept. If the target is acquired sooner and if the image processing estimate is accurate, then the surface defining the reachable targets is larger. This paper describes 1) the requirements for image processing, 2) acquisition, discrimination, and aimpoint problems, 3) algorithms that can be used, and 4) multi-microprocessor implementation of the algorithms.

2 Image Processing Algorithm Requirements

There are several conflicting requirements for achieving the highest probability of kill. On one hand, the target should be selected as soon as possible so the divert capability can be used early in the mission to maximize the size of the surface defining the reachable kill region on the target. On the other hand, at long ranges the target is a point source. If other point sources such as debris are present, target selection must be delayed until there is a high degree of confidence that the correct object is selected.

Once the target is acquired, the image processing must estimate the LOS direction toward a particular point in the target. The changes in that direction indicate cross range movement of the target relative to the KKV. A constant bias in the LOS estimate does not affect direction changes, so constant bias errors can be ignored. Other errors are due to 1) not detecting the target or not selecting which detected object is the target, 2) estimating the position of the selected target while it is still a point source, and 3) determining which point in a target image is the desired impact point.

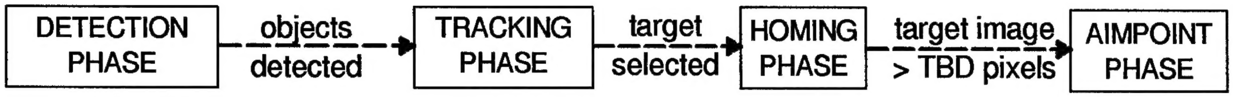

Figure 1. Algorithm phase transitions.

The requirements can thus be summarized as follows. 1) Detect all objects as early in the mission as possible, 2) Select the target object with a high confidence level in a timely manner, 3) Provide accurate aimpoint LOS, and 4) If the kill point on the warhead is different from the centroid of the target vehicle, select the warhead end of the target, as soon as it can be determined with a high probability, yet allowing sufficient time to divert to the kill point.

3 Detection, Selection, and Aimpoint Problems

3.1 Detection Of Target At Long Range

Again conflicting requirements must be resolved. The kill vehicle must be sufficiently small that it can be boosted to a large intercept volume with a minimum cost which conflicts with the need for a large aperture telescope to collect sufficient photons from a distant target. Complicating matters is noise, including pattern, white and one over *f* (*1/f*) noise [1], imperfections in the focal plane including dead detectors, and nonuniform responsivity of the detectors.

It is well known that signal–to–noise ratio (SNR) is increased by integration, so enhancing SNR is an obvious technique for increasing detection range. On–focal plane integration must be accomplished so as to preclude capacitor and multiplexor (MUX) saturation, and to accommodate available analog–to–digital converter (ADC) capability.

3.2 Target Selection

Generally, at desired acquisition ranges all objects in the field–of–regard (FOR) are point sources. The target must be discriminated from booster fragments and other debris, decoys, stars and other space objects such as satellites, etc. Closely spaced objects (CSO) must be either resolved or, until resolution is possible, included as potential targets.

The observable data for selecting the target is intensity, intensity rate, and apparent motion. Discriminants derivable from this data include tumbling or coning motion, passive range and closing rate based on ground based radar initial estimates. Multi–wave band data yields temperature, temperature rate, and emissivity–area product. Unfortunately, due to the limited telescope aperture, optical aberrations, and the noise in the readout, the target image is blurred and corrupted with noise. Accurately extraction of discriminants requires additional image processing to provide SNR enhancement.

If external target information is available, this external data must be fused into the discrimination process to optimize correct target selection.

3.3 Aimpoint Selection

If the target is a separated reentry vehicle (RV) it is not necessary to remove a large miss distance when the RV is resolved. If it is a tumbling missile, the end containing the warhead must be identified before the kill point on the warhead can be determined. Measurable characteristics of the target image include centroid, principal axis, length, width, area, and intensity. Data quality can be improved by removing blurring and by combining consecutive images to obtain more accurate target intensity and shape information.

Aimpoints are easily calculated if the target attitude is known. They lie on the principal axis of the target image, a certain portion of the way from the nose end to the tail end. The principal axis, the certain portion of distance, and the nose versus tail identification are based on 1) the rotation angle of the target's longitudinal axis' component in the focal plane, and 2) the aspect angle between the target's longitudinal axis' and a normal to the focal plane. These two angles define the target attitude.

A history of rotation and aspect angles is necessary when the target attains an attitude that is difficult to estimate. For example, if the aspect angle becomes zero (head–on case), then the rotation angle is undefined and is not required for aimpoint estimation. Since a symmetrical target's rotational motion constrains the aspect and rotation angles, they are not independent of one another and their histories can be advantageously estimated together in a smoothing filter.

In summary, a fundamental problem is to determine target attitude and target type so as to hit a precise kill point. Solving the problems of increasing target resolution and estimating target attitude enables selection of the aimpoint and prediction of its location at impact.

4 Detection, Selection, Aimpoint Algorithms

The phase transition of the algorithms is depicted in Figure 1. Objects are detected and tracked to increase the information available for discriminating the target. After the target is selected, the homing phase starts, and the centroid is provided to guidance. When the target image is large enough to identify the warhead, transition to the aimpoint phase results in providing the kill point location to guidance.

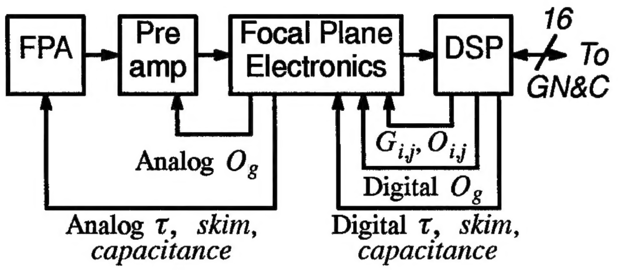

Figure 2. Variables set during calibration.

4.1 Detection Algorithms

Detection at the earliest possible time requires analog and/or digital integration to enhance SNR. Analog integration time and detector readout capability are increased by a skim voltage that removes electrons due to photons from telescope self emission. Capacitor size can be varied to increase the size of the readout. Digital calibration may not be required if detector linearity is good, and if off–focal plane integration accounts for background intensity, which includes pattern noise.

4.1.1 Calibration Figure 2 shows the variables that can be set during calibration. The variables integration time, τ, skim voltage, *skim*, and global offset, O_g, interact. An iterative procedure optimizes *skim* subject to variations in the skim control field effect transistors (FETs). If digital calibration is used, standard statistically based procedures determine a digital gain and offset G_{ij} and O_{ij} for detector *ij*, where *i* and *j* are the row and column numbers, respectively.

4.1.2 Off–focal Plane Integration

Off–focal plane integration sums frames to produce master frames at a lower frame rate [2]. Sensor motion causes subframes to have different viewing directions, so each subframe has its own spatial offset applied to compensate for that motion before the frame is added to the master frame. Each pixel of the resulting master frame contains the signal from a particular viewing direction. The FOR is represented by an inertially fixed 2D array of pixels and the output from each detector is added to the pixel that has the same viewing direction as the detector. A variation fixes the FOR relative to a target rather than to inertial space.

The summing increases SNR with respect to the white noise component, but the background must still be removed from the master frame. Off–focal plane integration assumes that the output of a given detector in a subframe remains essentially free of signal while the subframes are being accumulated. This output is estimated for each detector by taking a temporal average of the detector's readout values during the accumulation of a master frame and determines a background value for that detector. The background is then repeatedly subtracted from the master frame using the same motion–compensating spatial offsets as when the subframes were accumulated.

Off–focal plane integration algorithms estimate and remove background due to the scene, sensor self emission, and 1/*f* noise. They increase SNR by digital integration leading to earlier detection of objects. The sensor response in regions of interest is removed to the greatest degree possible by deconvolving the sensor response function from the image.

Figure 3 shows the result of off–focal plane integration. A single frame shows a strong signal, but nothing else other than noise. After off–focal plane integration, three low intensity signals are also present. Note that an offset evident in Figure 3 (a) is removed by the background removal as shown in Figure 3 (b).

4.2 Selection Algorithms

Selection algorithms are required for an operational KKV to discriminate a target from other objects in the FOV. Near term objects that must be discriminated include pieces of solid debris from the booster, the booster itself if it is separated from the warhead, and booster fragments. Eventually, boosters may include explosives to break it up along fracture

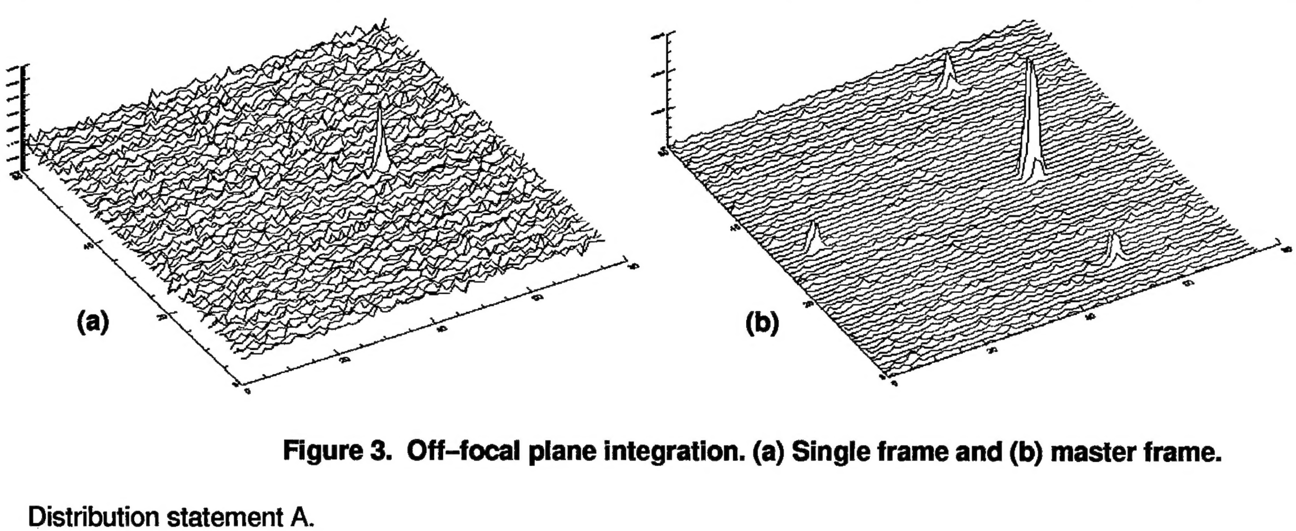

Figure 3. Off–focal plane integration. (a) Single frame and (b) master frame.

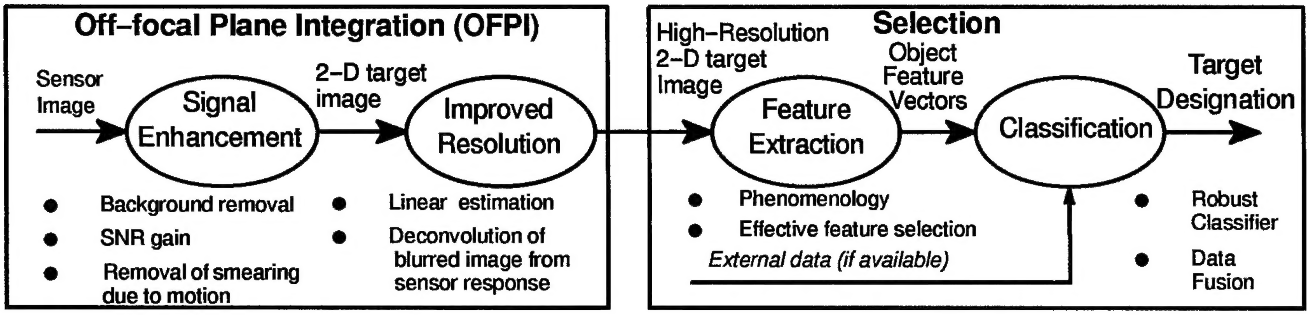

Figure 4. Algorithms used during selection.

lines introduced to control the size of the booster fragments. The fragments then must be discriminated from the warhead. Far term discrimination problems involve sophisticated threats that include decoys, balloons, aerosols, chaff, etc. in the objects deployed with the RV. All of these objects exhibit thermal, thermal rate of change, emissivity area, and intensity rate of change that enable discrimination of these nonlethal objects from the warhead.

4.2.1 Algorithm Interaction Figure 4 illustrates the interaction between off–focal plane integration (OFPI) and target selection. The features extraction function of Figure 4 identifies discrimination features based upon repeated angular position and intensity measurements, used for object differentiation by classification algorithms. Table 1 illustrates typical features. It is clear from this table that objects can not simply be discriminated using a single feature. In addition accurate estimation of an object's temperature requires multi–wavelength measurements.

Classification algorithms address the discrimination problem by using feature vectors of the objects in the seeker's FOR. These vectors are compared in the classifier using rules developed from training data to select the most probable target. This selection can be delayed only as long as is consistent with the allowable surface defining the reachable targets.

4.2.2 Tracking, feature extraction, classification A tracking algorithm determines a trajectory for each object so that the master and/or frame feature data is associated with the correct object. The features, as has been mentioned, are based on object motion, intensity, and motion/intensity rates. The features are estimated with the greatest accuracy possible by deconvolving the sensor response to determine trajectories to subpixel accuracy, and by estimating the amplitude with the greatest precision possible.

Classification requires features or discriminants to distinguish objects including celestial bodies, missiles with attached warheads, reentry vehicles, shrouds, tanks, tank fragments, balloons, chaff, aerosols, decoys, and other associated objects. Classification techniques based on phenomenology discriminants have been studied in the past [3]. Other discriminants based on multiple observations to identify kinematics of an object were also investigated.

Once the feature vector consisting of measurable discriminants is obtained, the type of object can be identified by classification process. Classification algorithms can be relatively simple for near term threats, but become increasingly sophisticated for far term threats. A near term classifier based on single color focal plane data uses object motion and intensity and their rates.

4.3 Aimpoint Algorithms

The aimpoint algorithms estimate the desired impact point based on the sensor's target image to within a small angle or, equivalently, to within a small number of pixels [5]. At longer ranges, a centroid of the target image is sufficiently

Table 1. Typical object features which allow target selection.

TARGET TYPE	OBSERVABLE BAND	DISCRIMINATION FEATURES					
		EMISSIVE AREA	TEMPERA-TURE	CONING ANGLE	PRECESSION PERIOD	DISPERSION VELOCITY ΔV	SPIN RATE
PBV	VISIBLE, MWIR, LWIR	LARGE	~400K	SMALL	VERY LOW	SMALL	LOW
RV	VISIBLE, LWIR	AVERAGE	~300K	SMALL	LOW	SMALL	VARIOUS
BALLOONS	VISIBLE, LWIR	AVERAGE	COOLS	VARIOUS	SLOW	VARIOUS	LOW
LREPs	VISIBLE, LWIR	AVERAGE	COOLS	VARIOUS	VARIOUS	VARIOUS	VARIOUS
FRAGMENTS	VISIBLE, LWIR	VARIOUS	COOLS	TUMBLES	TUMBLES	1/ MASS	TUMBLES

close to the position of the target's desired impact point. At closer ranges, when the target's attitude becomes known, then the position of the desired impact point is calculated.

The important parameters for aimpoint determination are target rotation and aspect relative to the KKV sensor LOS, (see [4], [5] for coordinate frame description), the nose end of the target, and target type. Nose end identification is particularly important if the target is a complete missile. With the rotation angle known, aimpoints can be estimated with sufficient accuracy while the aspect angle is still being determined. Target range is estimated from changes in the target image's width, area, and intensity. Range together with length of the target provide the target aspect angle.

4.3.1 Target Image Measurable Characteristics As mentioned earlier, measurable characteristics of the target image include: centroid, principal axis, length, width, area, and intensity. Consecutive images are combined to improve the quality of the image used to measure target characteristics. This is done by aligning the target image centroid positions and interpolating each image onto a common grid covering the target area. Bilinear interpolation is used for a value at a grid position from the values of pixels surrounding that position. The measurements are then made on this grid.

The centroid of the target image consists of the first moments of pixel intensities over a threshold. The principal axis orientation is calculated directly from the second moments of those pixel intensities. The length of the target image is obtained by evaluating intensity along the principal axis and applying a threshold to determine the end points of the axis. Similarly, the width of the target image is obtained by intensity thresholding along normals to the principal axis. The normals are placed at predetermined positions along the length of the axis. For a missile target, widths are calculated near the midpoint and averaged together. For an RV target, the largest width along the entire axis is used.

The area of the target image is the number of its pixels over threshold, and the intensity is the sum of its pixel intensities. Also, the intensity at a specific position in a target image is obtained by bilinear interpolation of the values of the four surrounding pixels.

Target rotation angle is the orientation of the target image's principal axis with respect to a focal plane axis. The aspect angle is estimated from the target image length together with either the target's range or the target image width.

4.3.2 Nose End Identification An example of an algorithm for nose end identification is an estimator of the width of the target image at both ends of the principal axis. The width at each end is the average of many widths measured along a fraction of the length. The two end widths are averaged over consecutive frames and the narrower end is designated the nose of the target.

5 Multi-microprocessor Implementation

This section describes real-time algorithm implementation using four TMS320C30 microprocessor devices. Selection algorithms are for a near term threat, so the primary processing difficulty is the OFPI.

5.1 Partitioning for Real-Time Implementation

In a focal plane output partitioning that accommodates a 256 x 256 pixel focal plane read at 120 Hz, each processor is given a region of the input image with the data allotted in the order read. The regions may overlap. For OFPI each microprocessor is given a horizontal strip comprising one-quarter of the image, as shown in Figure 5.

5.2 Hardware Configuration

Figure 6 illustrates the microprocessor hardware connections. The field programmable gate arrays (FPGAs) control movement of the pixels to the first in, first out (FIFO) devices. The shared memory allows for tight coupling among processors, and for data distribution.

The shared memory bus bandwidth is insufficient for transmitting entire images on a contiguous basis. Therefore, each microprocessor processes and summarizes its portion of the image. The summary information is passed to shared memory and integrated by higher level algorithms.

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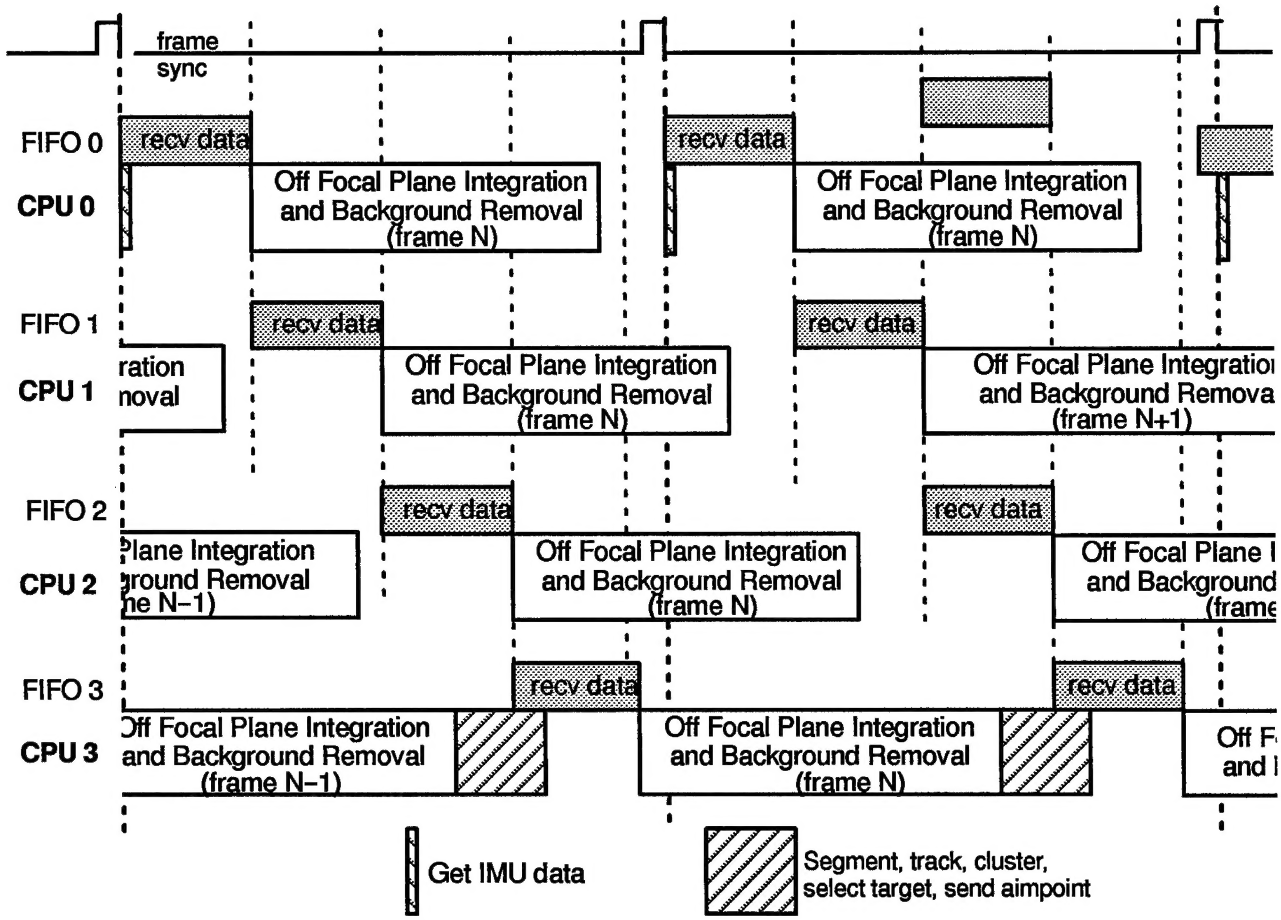

Figure 5. Off-focal plane integration timing diagram.

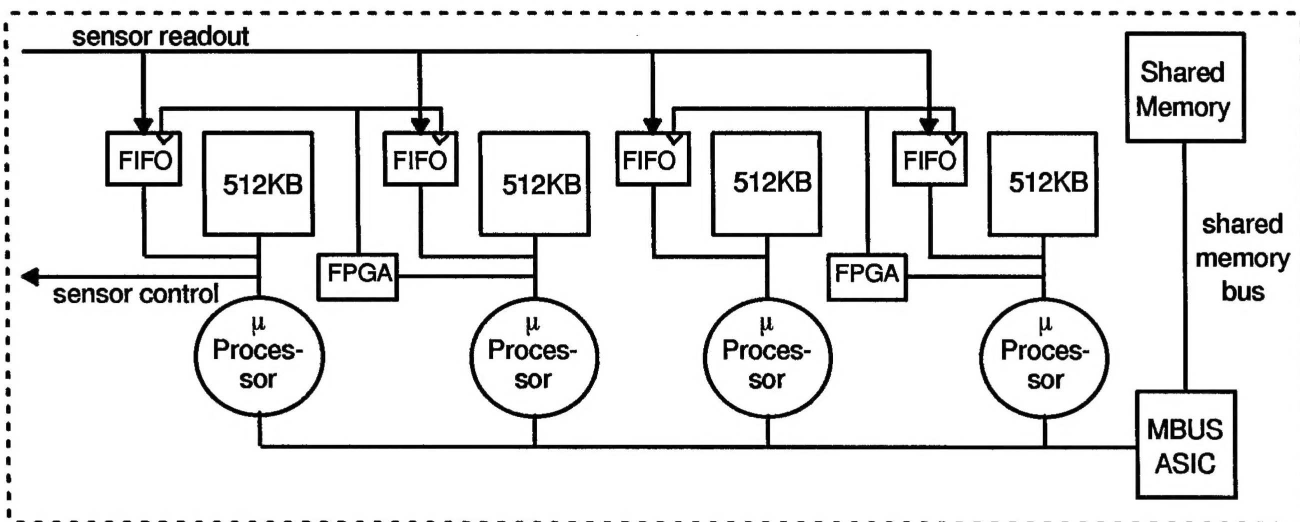

Figure 6. Programmable multiprocessor configuration to process algorithms.